ENGLISH

SOURCES OF MISMATCH IN UNSHADED PHOTOVOLTAIC COMMERCIAL ARRAYS

The Science Behind the Tigo Energy® Maximizer™ Series Product (MM-ES)

Tigo Energy Inc.
420 Blossom Hill Road
Los Gatos, CA 95032

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Tigo Energy, Inc.

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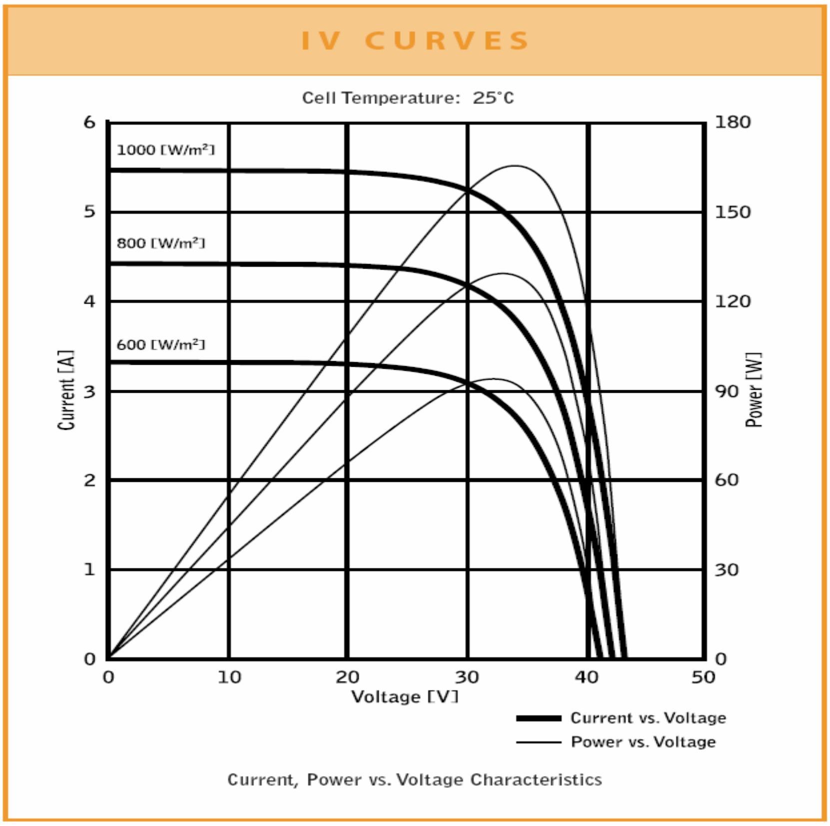
The purpose of this paper is to determine the sources of mismatch in unshaded commercial photovoltaic arrays and to determine the extent this mismatch lowers the system's energy production. Research has shown that mismatch is caused by manufacturing variance, thermal gradients within the array, uneven surface soiling, cloud shading and edge effects, failed bypass diodes, voltage drop in conductors, variable cell degradation and accumulated module wear and tear. It was determined that this mismatch typically represents 4-7% energy loss in a new, unshaded commercial array, with further losses growing over time.

INTRODUCTION

Module mismatch can have a significant impact on a solar photovoltaic plant's power production. When modules are not performing identically, the strong and weak modules have different power curves. As illustrated in Figure 1, a central inverter, optimizing for the entire array, must choose only one operating point for the entire array, which forces it to make compromises between strong and weak modules. Furthermore, as module I/V curves change dynamically and independently throughout the day, it becomes challenging for the inverter to achieve maximum energy yield from the array.

Figure 1: I/V Curves for Crystalline Silicon Modules

When an inverter must optimize two modules simultaneously, the power point is suboptimal for each.



However, while these relationships are well-understood in theory, there is a broad lack of understanding of the magnitude of module-level mismatch in unshaded commercial arrays. Many system designers assume that in the absence of shade, module-level mismatch is negligible. Without a proper understanding of the sources and magnitudes of module mismatch, system designers cannot make the appropriate cost-benefit decisions.

This paper will explain the common sources of module-level mismatch, as well as procedures for estimating their impact on an array's power production. This study will call on multiple disciplines, including semiconductor physics, industrial engineering, thermodynamics, and electrical engineering.

As the analysis below will show, module mismatch is an inherently site-specific attribute. It will always depend on the location of an array, and the specific components included in that array. Furthermore, the exact amount of mismatch will never be able to be perfectly predicted prior to building a solar installation – at best, designers will look at historical ranges of mismatch, and predict the amount of mismatch to be expected on the new array.

Every array is subjected to sources of mismatch. This paper seeks to provide those system designers with a toolkit for assessing those variables.

OVERVIEW OF MISMATCH DRIVERS

This paper is focused exclusively on well-designed, unshaded solar plants. Therefore, the only sources of mismatch detailed below are those that cannot be prevented through good design practices or component selection. These include:

1. **Manufacturing mismatch:** differences in module output driven by manufacturing variance
2. **Thermal gradients:** temperature differences across modules within an array
3. **Unevensoiling:** environmentalsoilingofmodules
4. **Cloud shading and refraction:** power spikes (both increases and decreases) due to clouds passing over an array
5. **Failed bypass diodes:** modules that are shipped from the factory containing failed bypass diodes
6. **Voltage drop:** mismatch in string voltage driven by voltage drop on the home run lines to the inverters
7. **Variable degradation:** silicon cells age at different speeds; compounding mismatch over time
8. **Accumulated wear and tear:** acute system problems that build up over time, such as mechanical or electrical faults

Each of these factors will be discussed below.

1) Manufacturing Mismatch

Manufacturing processes are not uniform. The nature of growing crystals and processing wafers and cells makes it nearly impossible to make cells with no variance between them. Inconsistencies in the semiconductor materials themselves (whether silicon or CdTe), impurities in the air, residue buildup in the manufacturing tools, and thermal drift all contribute to inconsistencies in manufactured modules. No two cells are ever identical.

This problem is well-understood, and has a standard solution: manufacturers "bin" their modules, selling them in ranges of power (typically +/- 3% to +/- 5%). Thus, when an integrator buys modules of a given power rating, they are actually buying modules with a range of power defined around a reference value (the nameplate rating).

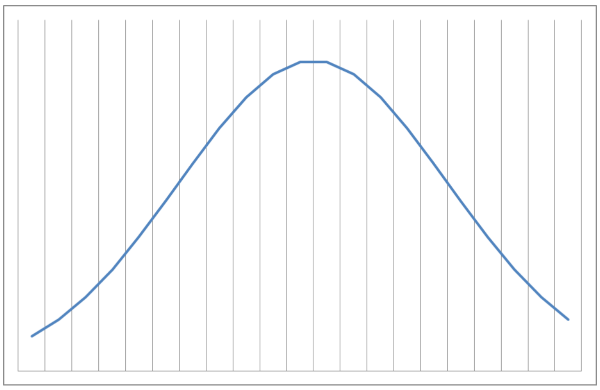
As shown in Table 1, a survey of the top modules shows that typical binning ranges are in the +/-2% to +/-3% range. This corresponds to an absolute delta of between 6 and 10% for the full binned range.

Figure 2: Typical module binning of top module manufacturers.

Bin Power Range	Number of Manufacturers Surveyed
3% total	2
5% total	3
6% total	3
10% total	2
Mean	5.9% range
Median	5.5% range

Source: Tigo Energy analysis

Since these bins are a cross-section of a normal manufacturing distribution, the module power within a binned range is typically evenly spread through the promised range. While these binning ranges are an elegant fix to the problem of manufacturing inconsistencies, they also represent a significant and measurable source of module mismatch.



Normal Distribution with Binned Ranges

1.1) Manufacturing Variance driven by Flash Test Error

In addition to the known mismatch from manufacturing variance, there is added measurement error due to the accuracy tolerances of the flash testing equipment. Most flash testing equipment has a target measurement error of +/- 1% (for a range of 2.0%), and a recent comparison 1 has shown the actual range of error is typically -1% to +1.3% (so a range of 2.3%). This makes the effective binning ranges even larger, as products on the edges of tolerance ranges can in practice be outside of the promised bin range.

1 "*Guidelines for PV Power Measurement in Industry.*" European Commission Joint Research Centre, Institute for Energy. April 2010.

There can also be considerable uncertainty in the cell temperature of the module during testing. Most manufacturers surveyed2 indicated that they typically have temperature tolerances of +/- 5% (see table below). And while manufacturers sometimes correct for ambient temperature, they often do not measure and correct for cell temperatures with each measurement. Thermal drift in the manufacturing process can lead to a wider error range than reported.

Figure 3: Manufacturing Temperature Ranges[3]

Temperature Range	Number of Manufacturers Surveyed
+/- 2%	1
+/- 5%	10
+/- 10%	1

Differences in cell temperature during flash testing can lead to measurement error, further increasing the manufacturing mismatch.

This means that modules can commonly have cell temperature differences of as much as 10%, which would impact the tested power production by 4-5%. Ultimately, this represents one more source of error for flash testing, and confounds the task of producing a tightly-binned set of modules.

Some installers will re-bin their modules before installation, re-sorting them into tighter groups based on their flash-test data. However, as shown above, the error tolerances in flash testing make re-binning a far less useful practice. It is our estimation that the improvement in system performance from re-binning is typically not worth the additional labor cost to re-bin the modules.

The impact of this binning mismatch can be seen in the recent testing performed by Photon Labs. In a laboratory environment, without any ambient sources of mismatch (e.g. soiling, thermal mismatch, or hard shade), the Maximizer System from Tigo Energy was still able to improve energy production by 3.2% in a system where the only source of mismatch was binning between the modules. This value (3.2%) is often used as a benchmark for energy losses due to module manufacturing variation.

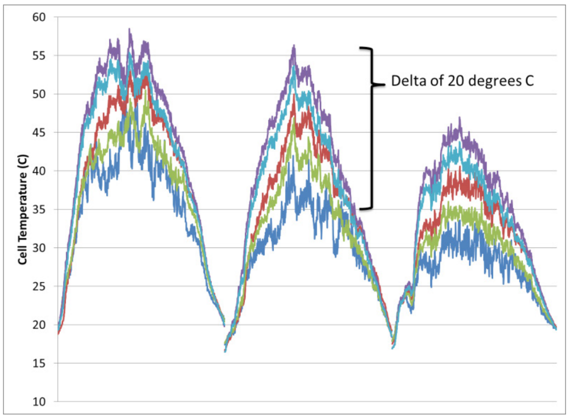
2 Ibid.

3 Source: "*Guidelines for PV Power Measurement in Industry*", European Commission Joint Research Centre

2) Thermal Gradients

Thermal variation within arrays can be a major source of mismatch. The difference between hot and cold modules can be as great as 20 degrees Celsius, consistently, as shown by the graph below, showing cell temperatures recorded from the same array on a flat commercial rooftop in Berkeley, CA

Figure 4: Cell Temperatures on Commercial Rooftop



Berkeley, CA, July 2009

The causes of thermal mismatch are relatively straightforward. Modules toward the edge of an array receive greater air flow than modules that are in the center and/or modules at the bottom (when the array is ground-mounted and tilted). Therefore, they run cooler than the modules in the center of the array, as show in Figure 5.

Figure 5: Module Temperatures on a Rectangular Array

68	71	71	72	72	74	75	73	73	70	71	72	68
69	67	74	77	79	78	77	78	78	75	70	70	71
72	71	74	76	79	85	81	82	75	77	73	73	70
67	68	74	77	78	79	77	75	77	80	74	69	68
65	68	71	71	74	75	72	72	74	72	72	72	67

This thermal mismatch leads directly to mismatch in power output. Most crystalline silicon modules have a thermal coefficient of power of approximately 0.45% per degree C. Thus, a 20-degree delta in temperature leads to a 9% difference in power output between hot and cold modules.

3) Uneven Soiling

Uneven soiling is another cause of mismatch. There are many different ways that modules can be soiled unevenly: dirt and dust buildup, organic debris, or bird droppings are some examples. Admittedly, soiling mismatch is challenging to accurately predict in advance. They are driven by very site-specific factors, such as the level of dust in the air, frequency of rainfall, frame dimensions of the module, and proximity to wildlife or plants such as trees or birds.

But regardless of the cause, uneven soiling will change the insolation that each module receives, leading to differing levels of power production. Furthermore, since this variables soiling tends to be persistent over the medium term (often 3-6 months), it will often lead to "hot spots" on the module, as spots of reduced efficiency lead to higher resistive losses in the module. This, in turn, can reduce the weak module's efficiency even further. Most developers must use historical data to estimate mismatch losses due to soiling; typical values range from 1 to 4%.

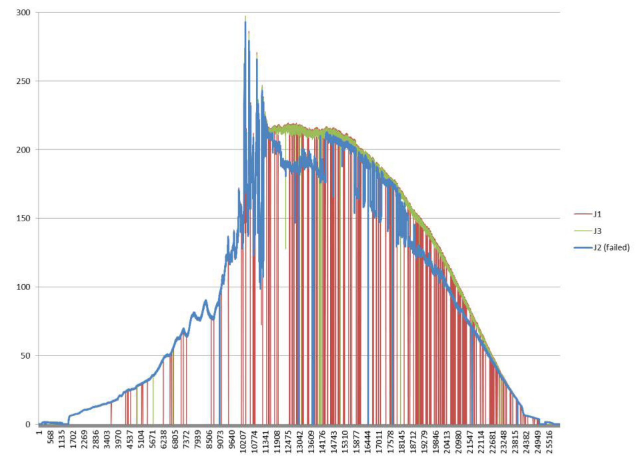
4) Cloud Cover and Refraction

Cloud cover is another common source of mismatch in solar arrays. High-atmosphere clouds create distinct shade patterns as they move over the earth. On a large enough array, these can lead to significant mismatches in the insolation, as they block direct normal irradiance (DNI).

Furthermore, as clouds move off of an array, they often create "edge effects", where they actually create spikes in the energy produced by the array. The array not only gets direct sunlight from the clear sky above it, but it also has additional sunlight reflected onto it through the white cloud that is right next to the patch of clear sky. This can lead to spikes in power of up to 125% of an array's rated maximum power. This is illustrated with the spike in power in Figure 6.

Figure 6: Power for Select Modules on a Commercial Scale Solar Plant in Santa Cruz

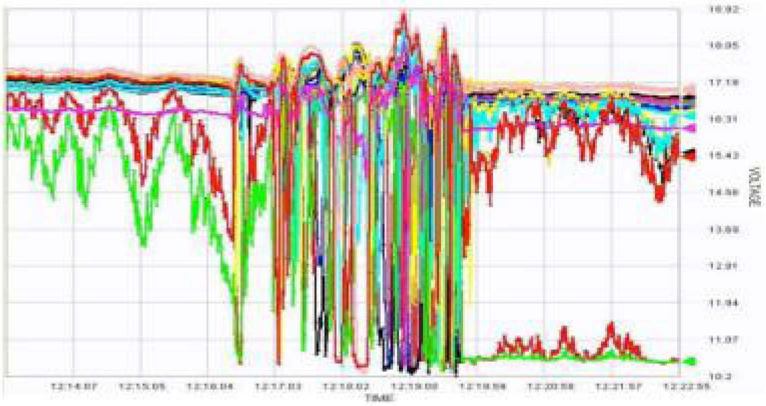
Note that these 240-watt modules briefly spike to 300 watts, equivalent to 125% of their rated power.



Both of these behaviors (cloud cover and cloud edge effects) create module mismatch which is extremely challenging for a central MPPT algorithm to effectively address. Note that, unlike module binning mismatch or thermal mismatch, cloud effects happen quickly. Therefore, the inverter is far more likely to get “stuck” on a sub-optimal power point for the array. This can be seen in Figure 7 below. Each line shows the voltage across modules in the same string, over time. The middle of the graph shows a time where a cloud moves over the array, causing the inverter’s MPPT algorithm to oscillate erratically for nearly five minutes. Then, when the inverter does stabilize on a current level, note that two of the modules have incorrectly triggered their bypass diodes (subsequently reducing their power output by 1/3).

Figure 7: Module Voltage Patterns During Transient Cloud Cover

In an array without module level power control, a central inverter struggles to maintain peak power



This example shows that even though the direct impact of transient cloud cover might be short in duration, it can cause disproportionate reduction in energy output due to the persistent limitations of the central MPPT algorithm.

5) Failed Bypass Diodes

One of our most consistent and surprising findings is the presence of failed bypass diodes in new modules. Across Tigo Energy installations, 0.3% to 0.5% of modules have had a failed diode upon delivery to the project site.

Without module level data, these failures are incredibly difficult to find. Most developers have never found failed diodes before using the Tigo Energy Maximizer System. Even installers who test line voltages during commissioning often don’t spot the failed diode. Under load, a failed diode only represents approximately 2-3% of the string’s voltage; this is easily within the margin of error for the measurement equipment. However, the direct loss of energy, plus the mismatch in power across strings in parallel, leads to losses that are typically 0.5% of the system power. These losses due to diode failure will, if undetected, persist for the full life of a system.

This pattern of failed diodes is visible across all types of manufacturers: large and small companies, and located in all parts of the world.

6) Voltage Drop

In commercial or utility systems, voltage drop is a source of mismatch that is commonly overlooked. As the system sizes grow and inverters get larger and larger, the distances from each of the strings to inverter can vary significantly.

Parallel mismatch is not as damaging as series mismatch, but the losses still accumulate. Assuming a standard block system design4, the table below shows typical power losses due to voltage drop in a commercial system:

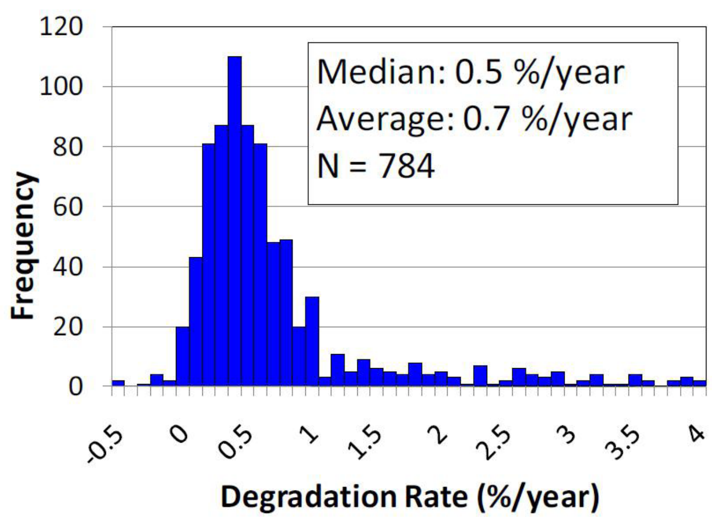
Figure 8: Voltage and Power Loss due to Long Conductor Runs

System Size (kW)	Maximum Home Run Distance (ft)	Avg. Voltage Drop (%)	Power Loss from Voltage Drop Mismatch (%)
50	179	0.7	0.0
100	264	1.2	0.0
250	524	2.5	0.3

7) Variable Degradation

One of the least -understood factors in solar plant development is the magnitude and nature of module degradation. As silicon modules degrade over time (a commonly acknowledged phenomenon), they do not degrade at the same rates. This is best illustrated in data provided by NREL. In their study of module degradation rates (analyzing over 780 modules), they found a wide difference in degradation rates between modules, shown in the histogram below:

Figure 9: Distribution Histogram of Module Degradation Rates



4 220W modules in strings of 12, module dimensions of 1.0m x 1.5m, #10AWG wire, and 50% ground coverage ratio

There are two important themes in the data shown above:

- A significant number of modules showed degradation patterns between 0% and 1%. While all of these are within the manufactured tolerances for degradation rates, the variation of degradation rates
  will still lead to significant mismatch over time. Five years into the system performance, that 1% variation per year will have led to a 5% difference in power production between modules throughout
  the entire array.

- A smaller proportion of modules (but not trivial) showed significant degradation rates of between 1% and 4% per year. Within 5 to 10 years, these modules will be significantly underperforming their peers (by as much as 20% to 40%), and will have a strong negative impact on system power production.

Note, importantly, that variable degradation may very well accelerate over time. As some modules degrade more than others in the early years, they have a lower peak power value than their peers. This, in turn, causes them to run “hotter” than the other modules, as they cannot convert all of their incident sunlight to energy. This added heat accelerates chemical processes such as ion migration (typically the cause of degradation in the first place), which subsequently accelerates the degradation going forward. It is highly likely that module degradation will actually increase over time for the weakest modules.

8) Accumulated Wear & Tear

Accumulated wear and tear is also a significant contributor to energy loss over time. Separating these sources of mismatch from variable degradation, as degradation is a “soft”, gradual mismatch that builds over time, whereas wear and tear are acute problems that happen more suddenly, and create much larger impacts on the energy production of a module, and on the system.

Figure 10 shows an eight-year-old system immediately after a retrofit of Tigo Energy’s Maximizer System. As can be easily seen from the color-coded power by module, there are several modules with significant problems. Specifically:

- 10 modules (3.0% of the system) are producing power at less than 90% of their peers
- An additional 12 modules (3.6% of the system) are producing power at less than 50% of their peers
- Two strings (7.2% of the system) had an open-circuit fault, and were not producing power at all
- An additional 76 modules (22.7%% of the system) are producing power at less than 20% of their peers

Figure 10: Module-level results from eight-year-old retrofit installation

The 22 heavily impaired modules had a significant impact on the energy production of the system. This is evidenced by the immediate impact that the Tigo Energy Maximizer System had on the array's energy production: the day of the retrofit, energy production increased by 25%. (Then, as the system owner sent modules back for warranty claims, the energy production grew by another 10%.) That 25% improvement is solely from the strong and weak modules being forced to work at the same current levels when on the same string.

There are a number of causes for this accumulated wear and tear. Over time rubber and polymer components can age and crack, glass modules can crack, humidity can short exposed circuits in the module junction box, and thermal expansion/contraction can cause mechanical connections (such as conduit joints) to separate.

CLOSING

Module-level mismatch can be properly understood if system designers allocate the time to properly characterize all of the factors. The eight factors described in this paper apply to solar plants of all sizes.

In fact, every source of mismatch described above is scale-independent for systems from 500kW to hundreds of megawatts. Most mismatch sources in large commercial arrays are identical to mismatch sources in utility-scale PV power plants.

The collective impact of these mismatch sources typically represents a 4-7% energy loss in a new array. However, these losses can be gained back by using module-level power electronics, such as the Tigo Energy Maximizer System. By keeping each module working at its individual peak power point, a module-level power maximization system can increase the energy output of any solar array. In addition, module-level data helps system owners spot anomalies or system failures as soon as they happen – and often diagnose the type of failure before even going onsite.

APPENDIX

Shading

While less common in commercial-scale systems, shade can sometimes lead to mismatch losses in arrays. While not the focus of this paper, recently-completed testing performed by Photon Labs confirms the larger magnitude of losses due to mismatch, and the corresponding benefit of module-level electronics. Testing a variety of shade patterns, Photon Labs found energy improvements from the Tigo Energy Maximizer system that ranged from 10% to 36%5 under various scenarios. For further reading, please see the separate white paper, "Photon Test Results", which can be found in the Tigo Energy Resource Center.

5 Photon International, "Optimizers under the Lamp", Podwils, Christoph. November, 2010.